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IMPROVEMENTS TO SINGLE-SOURCE MODEL VOLUME 1: TIME-CONCENTRATION RELATIONSHIPS

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IMPROVEMENTS TO SINGLE-SOURCE MODEL VOLUME 1: TIME-CONCENTRATION RELATIONSHIPS

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Prepared for

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SECTION I

INTRODUCTION

Reliable estimates of maximum 3-hour and 24-hour SO_2 concentrations due to power plant emissions are required for a variety of environmental assessment activities associated with air quality maintenance planning, fuel switching, plant siting and tall stack policy evaluations. Either of two methods are generally employed for the prediction of maximum SO_2 concentrations for these two averaging times. The first technique requires the prediction, by means of a diffusion model, of hourly SO_2 concentrations for an array of model receptor locations at a variety of distances and headings from the source. Running 3-hour means and daily 24-hour means are then obtained by averaging the predicted 1-hour concentrations. The resultant 3-hour and 24-hour concentrations are then sorted to find the highest and second highest values. This procedure is rather costly in terms of computer time since concentration predictions must be made for every hour of the year. The second method involves the calculation of a "worst hour" concentration based upon a critical windspeed and plume height.[1] This concentration is then used to estimate a "worst 3-hour" and a "worst 24-hour" concentration through the application of an appropriate peak to mean concentration ratio.

In the choice of a peak to mean ratio, one must obviously account for the wide range of possible ratios which could be selected. With a large number of site years of data one could construct distributions of ratios of highest 1-hour to highest 3-hour and 24-hour concentrations for the year and select some percentile of this distribution as the peak to mean ratio to be used. The choice of a given percentile would be dictated by the desired degree of conservatism in the 3-hour or 24-hour estimate,

with peak to mean ratios of 1 being the extreme example. In the absence of a large number of site years of data, peak to mean ratio distributions may be constructed by use of all hourly measurements. In two earlier EPA reports[2,3] GCA analyzed frequency distributions of peak 1-hour to average 3-hour and peak 1-hour to average 24-hour SO_2 concentration ratios based upon hourly concentration measurements at four separate power plant sites. In all cases the peak to mean ratios were calculated in terms of concentrations that have been corrected for background concentration which was determined on an hourly basis from an average of measurements at upwind receptor locations. One drawback to this procedure is that the ratio distribution is heavily influenced by those "peak" concentrations near the background level which occur when the receptor is not influenced by the point source plume. The purpose of the present study was therefore to examine the effect upon ratio distribution statistics if only peak concentrations above a certain cutoff value were analyzed, and thereby ensure that ratios used for the estimation of maximum 3-hour and 24-hour concentrations from maximum 1-hour values will be derived from ratio frequency distributions associated with the highest percentile of 1-hour concentrations. The following percentile limits for the peak concentration were tested: 95, 98 and 99. The actual concentrations associated with these percentile limits were determined for each plant site through an examination of the cumulative frequency distribution of background subtracted concentrations for all receptor sites taken as a whole. Statistics of peak to mean ratio distributions included in the analysis were the arithmetic mean, arithmetic standard deviation, geometric mean, geometric standard deviation, median and correlation between peak concentration and associated peak to mean ratio.

In the next section of this report we shall describe the plant site characteristics and the meteorological and air quality data bases used in the study. This will be followed by a discussion of the ratio distributions and their associated statistics, including an analysis of

the variation of these parameters for different plant sites and peak concentration cutoffs. We shall then conclude with a discussion regarding the general applicability of these results to other point sources.

SECTION II

SITE AND DATA BASE DESCRIPTIONS

In this section we shall describe the site characteristics, SO_2 monitoring program and meteorological data base for each of the four power plants included in the study. Each topic will be covered on a plant-by-plant basis.

CANAL PLANT

Site Description

The Canal Plant is located on the south side of the Cape Cod Canal about 1.6 kilometers from the entrance on Cape Cod Bay (Figure 1). The surrounding terrain is gently rolling with elevations generally below 60 meters above mean sea level. The highest elevations in the area are about 90 meters above sea level in the western end of the Cape. Most of the area is covered with scrub pine forests and low vegetation.

Data for the study were collected in 1971. During that year, the plant consisted of a single oil-fired unit with a generating capacity of 560 megawatts. The top of the stack was about 91 meters above grade and 5.6 meters in diameter. The main power plant structure to the north of the stack totally enclosed the turbine generator and boiler. The roofs of the turbine and boiler rooms were about 30 meters and 59 meters above grade respectively. Stack and boiler data are given in Table 1. The 1971 monthly percent sulfur content of the fuel used at the Canal Plant is given in Table 2.

Figure 1. Map of eastern Massachusetts and Rhode Island showing the location of the Canal Plant. Meteorological observations were used from Quonset Point Naval Air Station and Nantucket Island

Table 1. PLANT CHARACTERISTICS

Characteristic	Plant						
	Canal	Stuart	Muskingum		Philo		
	Stack 1	Stacks, all four	Stack 1	Stack 2	Stack 4	Stack 5	Stack 6
Stack height, m	91	244	251	251	81	81	84
Diameter, m	5.6	6.0	7.6	6.7	5.2	3.9	2.6
Velocity, m/sec	19.8	22.2	28.5	24.8	4.5	7.7	29
Temperature, ^{o}K	469	373	430	425	458	458	433
Number of boilers per stack	1	1 each	4	1	2	2	1
Maximum generating capacity per stack, MW	560	610	876	591	166	166	125
Average per stack, MW	-	439	748	487	114	128	84
Plant total, MW	560	2440	1467		457		
Plant average, MW	-	1318	1235		326		

Table 2. MONTHLY PERCENT SULFUR CONTENT OF FUEL

Month	Canal	Stuart	Muskingum	Philo
January	2.0	1.8	4.9	3.9
February	1.9	1.6	4.8	4.8
March	2.1	1.8	4.8	4.7
April	1.9	1.7	4.5	4.4
May	2.1	1.8	4.7	3.3
June	2.1	1.6	5.0	3.2
July	2.1	1.5	4.7	2.6
August	2.0	1.5	4.7	3.2
September	1.9	1.5	4.3	3.2
October	0.9	1.5	4.6	2.4
November	1.0	1.8	4.5	2.6
December	0.9	2.1	4.4	3.7

Overview of Monitoring Program

SO_2 concentrations are measured at four locations on a continuous basis with Ultragas SO_2 Analyzers manufactured in Germany by H. Wosthoff. These instruments measure sulfur dioxide by the increase in conductivity of an acidified hydrogen peroxide solution and have a full scale reading of 0.4 ppm. The instruments do not conform to the reference method for sulfur dioxide or to any of the specified equivalent methods.[4] They have, however, been extensively studied and one comparison noted a correlation coefficient of 0.99 with the West-Gaeke method.[5] The instruments used provide a continuous real-time chart trace and a tape printout giving date, time, and average concentration over consecutive 30 minutes. The sensitivity of the instrument in combination with the chart recorder is approximately 0.005 ppm. The locations of the SO_2 monitors with respect to the Canal Plant are given in Figure 2 and Table 3.

Meteorological Data

Bendix-Friez Aerovanes are used to provide local windspeed and direction data. Through July 1971, the principal source of wind data was the Aerovane mounted on a 12.2 meter mast located on the 58.8 meter boiler-room roof. Since July 1971, wind data are obtained from a second Aerovane installed on a 44 meter tower near the top of Telegraph Hill approximately 5 kilometers south-southeast of the Canal Plant.

STUART PLANT

Site Description

The J. M. Stuart Plant is located in southwestern Ohio on the Ohio River, about 9 kilometers southwest of Manchester, Ohio, and 4 kilometers east of Maysville, Ohio (Figure 3). It is located near the center of this river valley. The ridges on either side of the valley are about

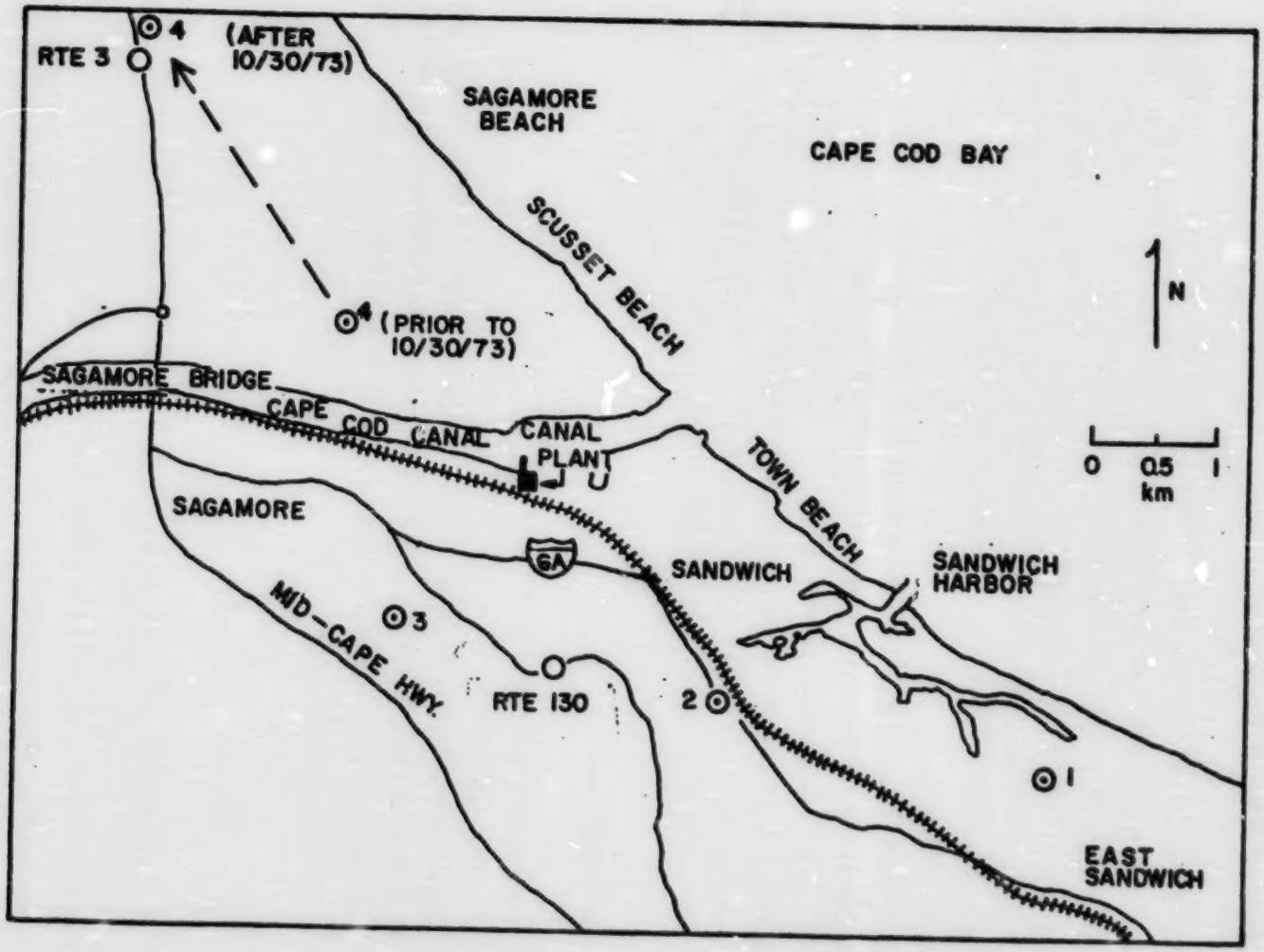

Figure 2. Sketch of the Canal Plant area showing the locations of the four automatic SO_2 stations by the symbol ⊙

Table 3. SULFUR DIOXIDE MONITOR STATIONS

Plant	Station		Distance, km	Heading, degrees	Elevation above stack base, m
	No.	Name			
Canal	1		4.7	119	10
	2		2.3	138	4
	3		1.4	224	40
	4		2.0	312	20
Stuart	1	Boone	2.4	35	115
	2	Brudysville	6.6	15	85
	3	Bentonville	13.4	28	121
	4	Manchester	8.7	49	-7
	5	Maysville	3.8	279	-4
	6	Rectorville	8.4	156	115
	7	Somo	5.0	220	115
	—	Top of stacks	—	—	244
Muskingum	1	Beverly	5.3	140	64
	2	Hackney	4.3	40	82
	3	Rich Valley	8.3	35	101
	4	Caldwell	19.6	35	128
	—	Top of stacks	—	—	251
Philo	1	Philo	1.7	174	3
	2	Fox Run	4.8	166	2
	3	Irish Ridge	5.0	235	99
	4	Duncan Falls	1.3	343	12
	5	Salt Creek	6.0	25	26
	6	Indian Run	4.2	334	63
	—	Top of stacks	—	—	81

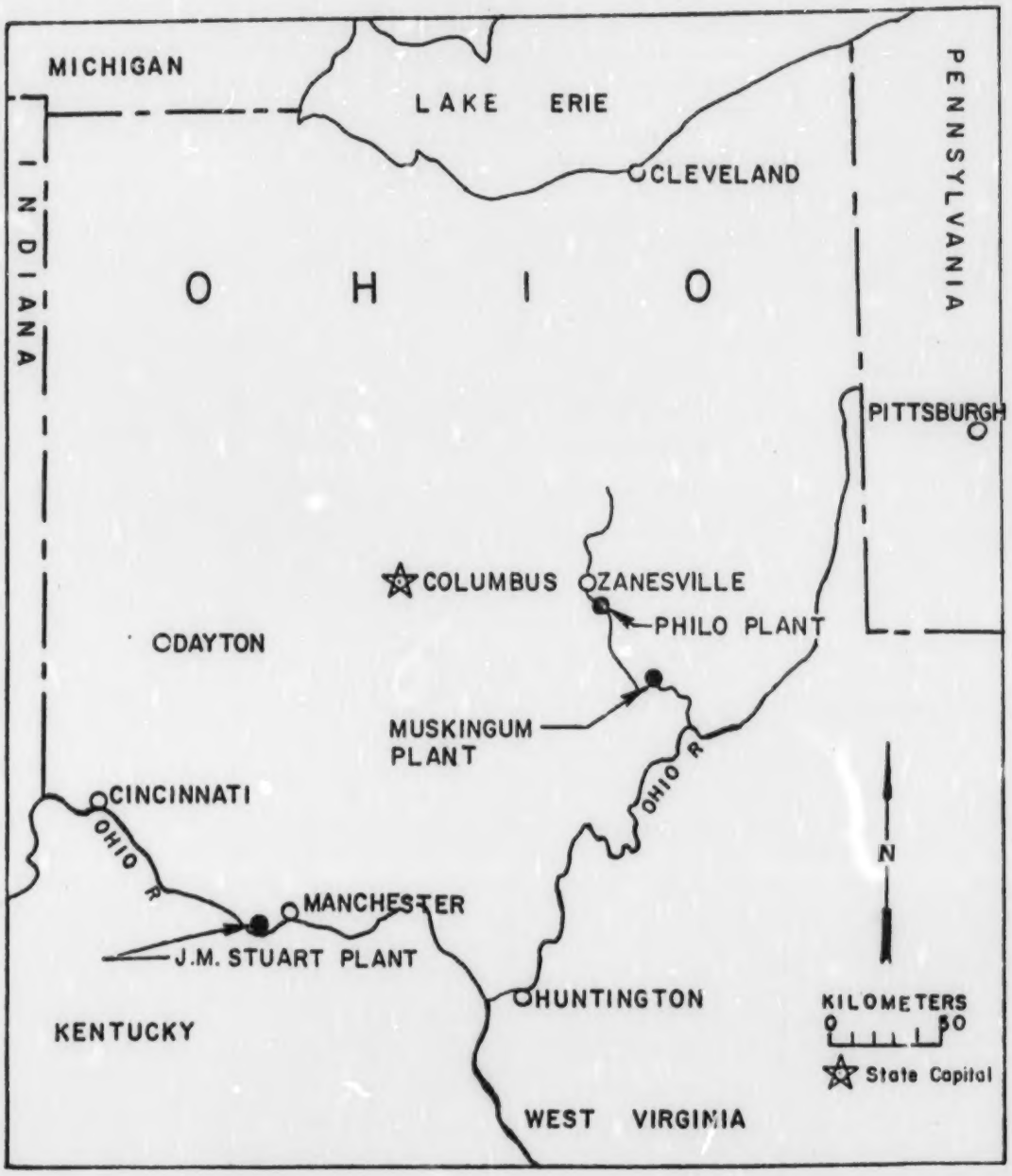

Figure 3. Map of Ohio and surrounding states showing the locations of the J. M. Stuart Plant, Philo Plant, and Muskingum River Plant

115 meters above the valley floor and 700 meters from the power plant. The 244 meter stacks rise 130 meters above the surrounding countryside. The data were collected during the 1-year period from January 1, 1973 to December 31, 1973. The plant consists of four identical coal-fired boilers with a capacity of 610 megawatts each. However, one boiler was under repair during the entire year so that the total generating capacity was only 1830 megawatts. The yearly average generating load was 1318 megawatts, or 72 percent of available capacity. Stack and boiler data are given in Table 1. Monthly percent sulfur values for 1973 are given in Table 2.

Overview of Monitoring Program

The monitoring network consists of seven sulfur dioxide monitoring stations (Figure 4 and Table 3). The monitor at Station 2 was moved to Station 4 on March 10, 1973, and the monitor at Station 7 was discontinued on June 17, 1973. Therefore no data is available at Station 2 for 9 months, Station 4 for 3 months, and Station 7 for 6 months. The instruments were all Leeds & Northrup Company, Catalog No. 7860-SW, Aeroscan Air Quality Monitors, purchased in 1968. The sample was obtained by passing ambient air taken from 5 feet above ground level, through an absorption column along with an absorption solution. The sample analysis method was by electrolytic conductivity. Data were taken continuously and listed every hour. Electrical calibration tests were performed weekly for zero and half scale operation. Overall calibration tests were made every 6 months at 0.2 ppm using the permeation tube method whose accuracy is traceable to the U.S. Bureau of Standards. There were some additional hours of missing data due to (1) loss of electrical power; (2) periods of calibration and maintenance; and (3) system failures caused by presence of foreign material in the sample flow, pump failure, loss of ink supply, failure of the conductivity cell, etc.

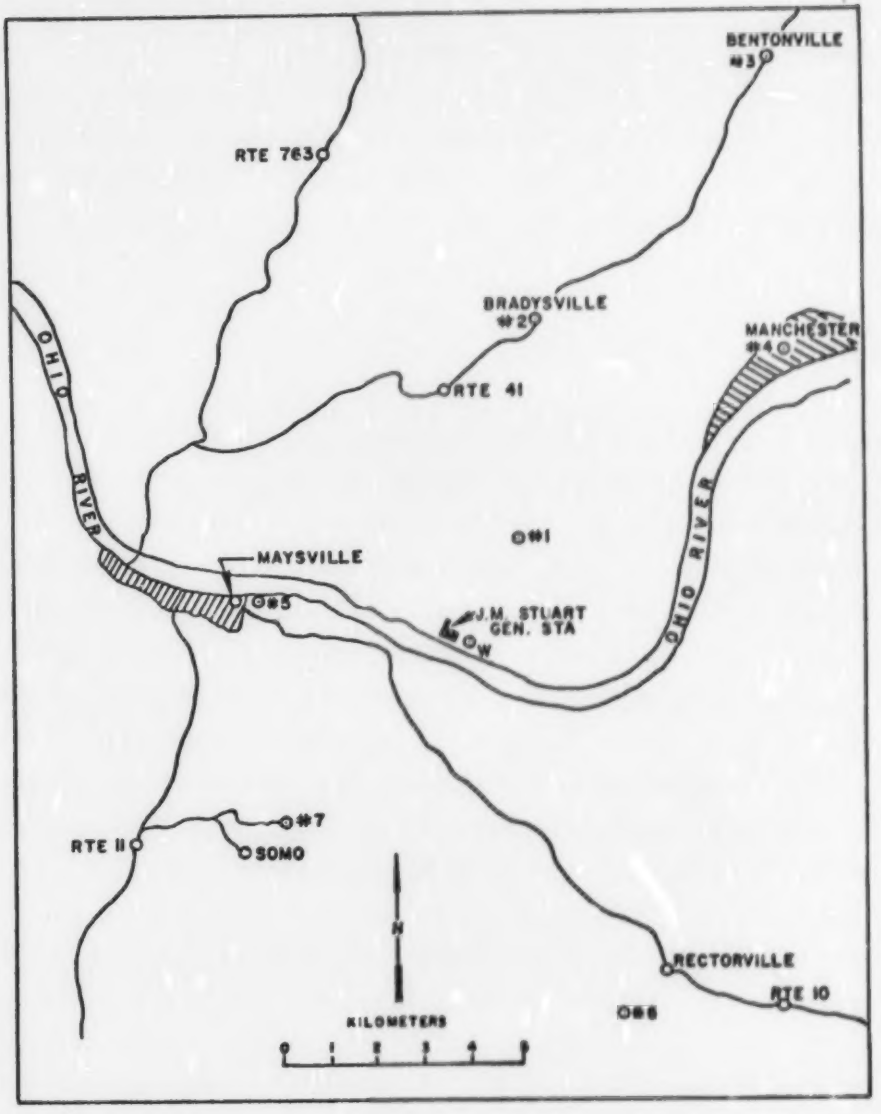

Figure 4. Sketch of the J. M. Stuart Plant area showing the locations of the seven automatic SO_2 monitoring stations

The manufacturer's performance accuracy specifications are as follows. In a typical ambient atmosphere which includes the normal interfering gases, this instrument has:

- Zero drift = 2 percent of full scale per week
- Sensitivity drift < 1 percent of full scale per week
- Reproducibility < 1 percent of full scale
- Sensitivity = 0.01 ppm
- Recorder error < 0.5 percent of full scale
- Range = approximately 0 - 1 ppm

Meteorological Data

The meteorological instrumentation at the J. M. Stuart Plant consists of a Bendix-Friez windspeed and direction device mounted 40 meters above the ground on the coal stacking tower.

MUSKINGUM PLANT

Site Description

The Muskingum Plant is located in southeastern Ohio on the Muskingum River about 6 kilometers northwest of the town of Beverly. Figure 5 indicates the location of the plant, the SO_2 monitoring sites, and the surrounding towns. The plant is in the river valley about 500 meters from the valley walls which rise about 75 meters above the valley floor. The two 251 meter stacks are 640 meters apart and extend about 185 meters above the surrounding terrain. During 1973 the plant consisted of five coal-fired units with a total capacity of 1467 megawatts (Table 1). Percent sulfur content of the fuel for 1973 is given in Table 2.

Figure 5. Sketch of the Muskingum Plant area showing the locations of the four automatic SO_2 monitoring stations

Overview of the Muskingum Monitoring Program

Four sulfur dioxide monitoring stations make up the monitoring network (Figure 5 and Table 3). Data were available from all stations for January 1 to November 21, 1973. During the entire year of 1973, Station 1 missed 57 days and the other three stations missed approximately 41 days in total. The monitors were the same type used at the Stuart Plant, with the same calibration procedure, except that they were automatically zeroed once a day.

Meteorological Data

There were two wind monitoring stations at the Muskingum Plant consisting of Bendix-Friez Aeronave windspeed and direction devices. One station was located 33 meters above ground at Beverly, and the other at the Hackney SO_2 monitoring station, where the wind monitors were located 22 meters above ground. The data from Hackney was used in this study, as it was higher and common to more stations, but Beverly data was used when the Hackney system was not recording.

PHILO PLANT

Site Description

The Philo Plant is a 457 megawatt facility located in eastern Ohio on the Muskingum River in the town of Philo, about 11 kilometers to the southeast of Zanesville, Ohio (Figures 3 and 6). The plant is roughly 500 meters from the valley walls to the east and west, although the valley widens to the north. The three stacks are approximately 82 meters high and rise about 10 meters above the surrounding terrain. During 1974, the period of this study, the plant consisted of five coal-fired boilers feeding into three stacks (Table 1). Percent sulfur content of the fuel by month for 1974 is given in Table 2.

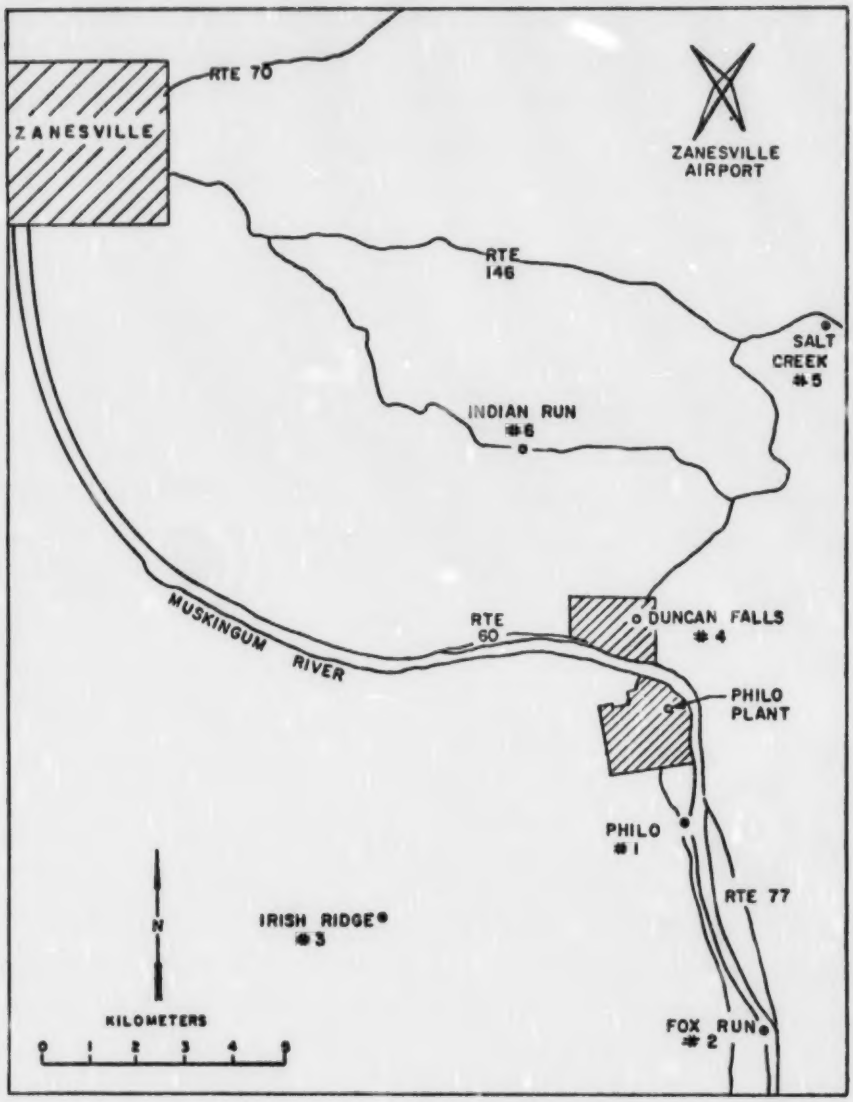

Figure 6. Sketch of the Philo Plant area showing the locations of the six automatic SO_2 monitoring stations

Overview of the Philo Monitoring Program

The monitoring system in 1974 was made up of six Malloy continuous SO_2 samplers, located as shown in Figure 3 and Table 3. Data were recorded for all of 1974 except the following:

Station Outages

Station 1	First 91 days of year	
Station 4	First 91 days of year	
Station 6	Second 91 days of year	April to July

The monitoring system maintenance and data acquisition were performed by Environmental Research and Technology in Lexington, Massachusetts.

The instruments were calibrated every 6 months in Lexington and zeroed every night by computer. These monitors were made by Malloy and have the following specifications:

Malloy SO_2 Sensor Specifications

Range	0-1 ppm
Sensitivity	0.005 ppm
Noise	± 0.5 percent FS
Response lag	< 15 seconds
Rise time to 90 percent	< 30 seconds
Fall time to 90 percent	< 30 seconds
Precision	± 1 percent FS
Accuracy	± 1 percent FS
Zero drift	±0.01 ppm/day
	±0.02 ppm/3 days
Span drift	±0.01 ppm/day
	±0.02 ppm/3 days
Linearity	± 1 percent FS

Meteorological Data

There were three meteorological stations at Philo:

1. Irish Ridge Upper - elevation 140 meters above plant base, (50 meters above ground). This station monitored wind-speed and direction, and temperature difference from the lower station.

2. Irish Ridge Lower - elevation 104 meters above plant base, (11 meters above ground). This monitor measured wind speed and direction, and temperature.

3. Duncan Falls - elevation 14 meters above plant base, (6 meters above ground). Only wind speed and direction were recorded here.

The instrumentation system components included:

- Climet WD-012-10 Vane and WS-011-1 Anemometer
- Climet 015-2 and 3 Thermister
- Bendix T20-510072-6 3 blade Impeller

The system was maintained by Environmental Research and Technology, Inc. The first 100 days of meteorological data were not recorded for 1974. The primary station for wind direction measurements was Irish Ridge Upper. If this station was not operating, wind direction data was taken from Irish Ridge Lower or Duncan Falls.

SECTION III

ANALYSIS OF CONCENTRATION RATIO DISTRIBUTIONS

To ensure that the ratio distributions reflect only the influence of the power plant in question, hourly SO_2 measurements were corrected for background contributions from other sources. The background was assumed to be the average of those concentrations from stations outside of a 90° sector centered about the wind flow vector, as measured by the plant wind vane. This average background concentration was subtracted from the concentration measurements for all stations for that hour. Any negative concentration values resulting from the background subtraction were set equal to zero. In the case of missing data or calms, the last recorded wind direction was assumed to persist until a station reported a concentration over 0.1 ppm, in which case the wind was assumed to blow towards that station until a wind direction was recorded or another station reported a concentration over 0.1 ppm.

These corrected concentrations were then analyzed to obtain peak 1-hour to average 3-hour and peak 1-hour to average 24-hour concentration ratios. For the calculation of the 1- to 3-hour ratios, 3-hour intervals were allowed to overlap, giving a new ratio for each hour. In the case of the 1- to 24-hour ratios, however, only one ratio was evaluated for each calendar day. If one of the hourly concentrations to be used in a 3-hour or 24-hour average was missing, then that ratio was omitted from the analysis. Cases where the 3-hour or 24-hour average concentrations were zero were also omitted from the analysis. Both 1- to 3-hour and 1- to 24-hour ratios were sorted into 200 bins to generate a frequency distribution.

The main purpose of this study was to examine the effect upon the peak to mean ratio distributions of restricting the peak 1-hour concentration to be above a certain threshold. Separate frequency distributions of peak to mean ratios were developed for 1-hour SO_2 concentrations (corrected for background) above the following 1-hour concentration percentile values: 0, 95, 98, and 99. Frequency distributions of measured minus background concentrations were previously calculated[2,3] for the Canal, Stuart, Muskingum and Philo plants. An example of one such distribution is presented in Figure 7.

In Figures 8 through 23 we present log-probability plots of peak 1-hour to average 3-hour and peak 1-hour to average 24-hour concentration ratio cumulative frequency distributions for each plant and each peak 1-hour concentration cutoff. The statistical parameters associated with these distributions are given in Table 4.

A cursory examination of these frequency distributions reveals two rather obvious features. By definition the frequency distributions for the 1- to 3-hour and 1- to 24-hour concentration ratios are bounded by 1 and 3 and 1 and 24, respectively. Also, the distributions for both the 1- to 3-hour and 1- to 24-hour ratios are described rather well by a log-normal function especially for high peak concentration cutoffs. The following observations are based upon a more detailed analysis of the distribution plots and tabulated statistics:

- For the Stuart and Muskingum plants there appear to be a significant number of 1- to 3-hour peak to mean ratios exactly equal to 1. This feature persists even as the threshold for the peak concentration is increased. In the case of the Canal and Philo plants no peak to mean ratios equal to 1 were observed once the peak concentration threshold was increased to the 98th percentile value. This property of the ratio distributions may be traced to the fact that SO_2 concentrations (ppm) were reported to 3 decimal places for the Canal and Philo plants, but only to 2 decimal places for the Stuart and Muskingum plants. Therefore, variations in concentrations at the ppb level were not as likely to be observed at Stuart and Muskingum.

- Another feature of the cumulative frequency distributions is the reduction in the number of higher ratios as the peak concentration limit is increased. This is true both for the peak 1-hour to average 3-hour and peak 1-hour to average 24-hour ratios. The primary reason for this reduction is that as the lower limit for the peak concentrations is increased, the peak to mean ratios under analysis would apply to those time periods for which the plume is actually influencing a given receptor location. There is less likli-hood that a high 1-hour concentration will occur in a 3-hour sequence with two very low concentrations. The latter situation was a rather common occurrence when there was no lower limit to the peak concentration. For example, consider the following situation: SO_2 concentrations of 0.01, 0.01 and 0.03 ppm are reported during a 3-hour period at a particular receptor location and the corresponding calculated background concentrations based upon measurements at upwind receptor locations are 0.01, 0.02, and 0.01 ppm, respectively. According to the background subtraction scheme we have employed the corrected concentration would be 0.0, 0.0 and 0.02 ppm which yields a peak 1-hour to average 3-hour concentration ratio of 3.

- For the Stuart and Muskingum Plants the geometric means of the peak 1-hour to average 3-hour concentration ratios decrease when higher lower bounds for the peak concentrations were established. For the Philo and Canal Plants a corresponding increase was observed. The decrease in peak 1-hour to average 3-hour concentration ratios for increasing peak concentration limit at Stuart and Muskingum is due in part to the 0.01 ppm threshold for hourly SO_2 measurements at these to sites.

- If one restricts the analysis to the highest peak (99 percentile) 1-hour concentrations the geometric means of peak 1-hour to average 3-hour concentration ratios are distinctly higher for the Philo and Canal Plants than for the Stuart and Muskingum facilities. The corresponding trend toward lower peak 1-hour to average 24-hour concentration ratios with distance is much weaker.

- As the 1-hour peak concentration is increased both ratio distributions become smoother although fewer ratios have been included in the analysis. In the cumulative distribution for the zero percentile peak concentration cutoff this is especially evident for a 1- to 3-hour ratio of 1.5. This peak in the frequency distribution is due to the large number of combinations of three discrete consecutive

1-hour concentrations which can cause a ratio of 1.5. If the three concentrations are x_1, x_2, x_3, and x_1 is the concentration for the peak hour then if $x_2 + x_3 = x_1$ the ratio will be 1.5. Examples of this would be (0.01, 0.01, 0), (0.01, 0, 0.01), (0, 0.01, 0.01), (0.02, 0.02, 0), etc.

It should be pointed out that the statistical relationships for the peak 1-hour to average 3-hour concentration ratios presented in Table 4 are not strictly valid since a peak 1-hour concentration and the associated overlapping 3-hour average concentration are not independent. The relatively high correlation between consecutive 1- to 3-hour peak to mean ratios is roughly equivalent to including a given ratio in the analysis three times. This is especially true for those cases where we have required that only those peak concentrations above a certain threshold be included in the analysis. This problem could be circumvented by tabulating the ratio between the highest 1-hour concentration for a day and the highest 3-hour average concentration for that day, with the requirement that the highest 1-hour value occur during the 3-hour period chosen for the highest 3-hour average. The major difficulty with this procedure, however, is that it is not consistent with the definition of the 3-hour mean as a sliding average. Nevertheless, it would be a valuable exercise since it would determine whether the distribution statistics such as the geometric mean and geometric standard deviation are strongly influenced by the interdependence between successive ratios.

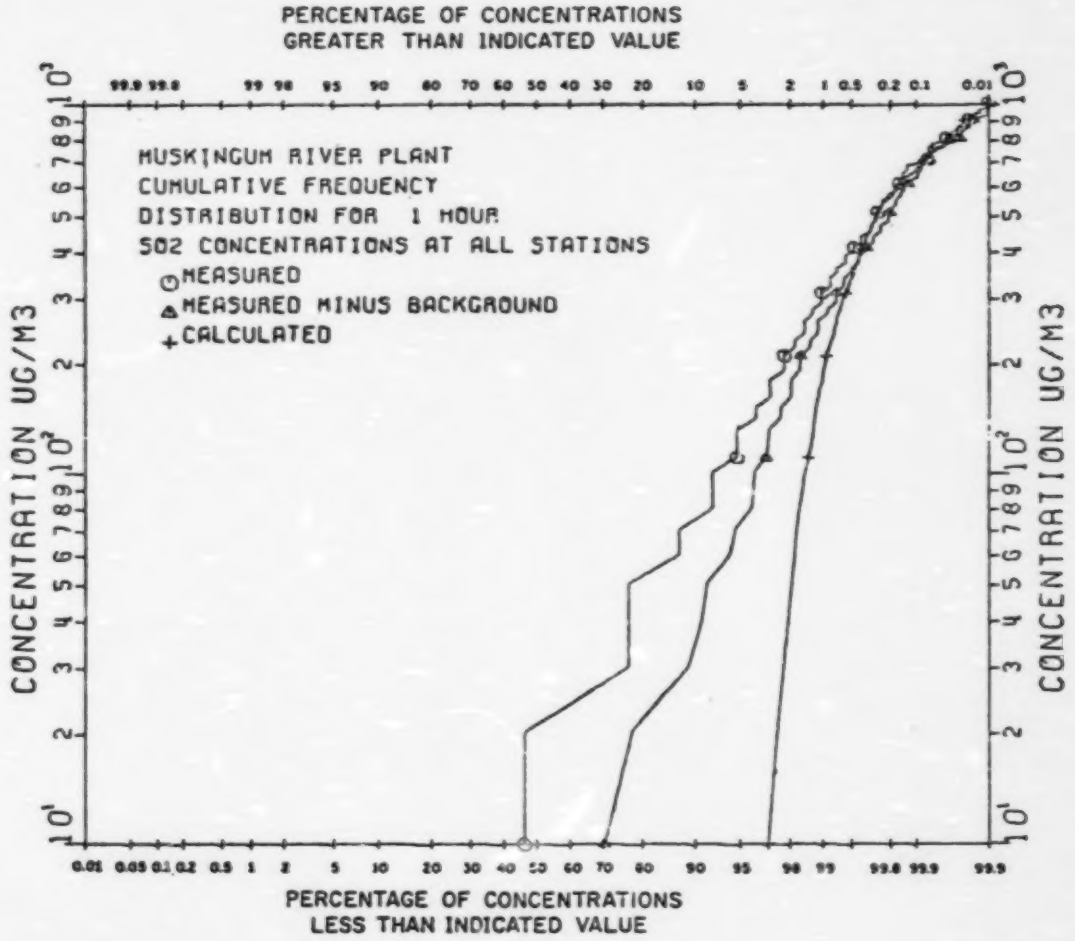

Figure 7. Muskingum River plant cumulative frequency distribution for 1-hour SO_2 concentrations at all sampling stations. Number of measured concentrations = 30,622; number of calculated concentrations = 61,320

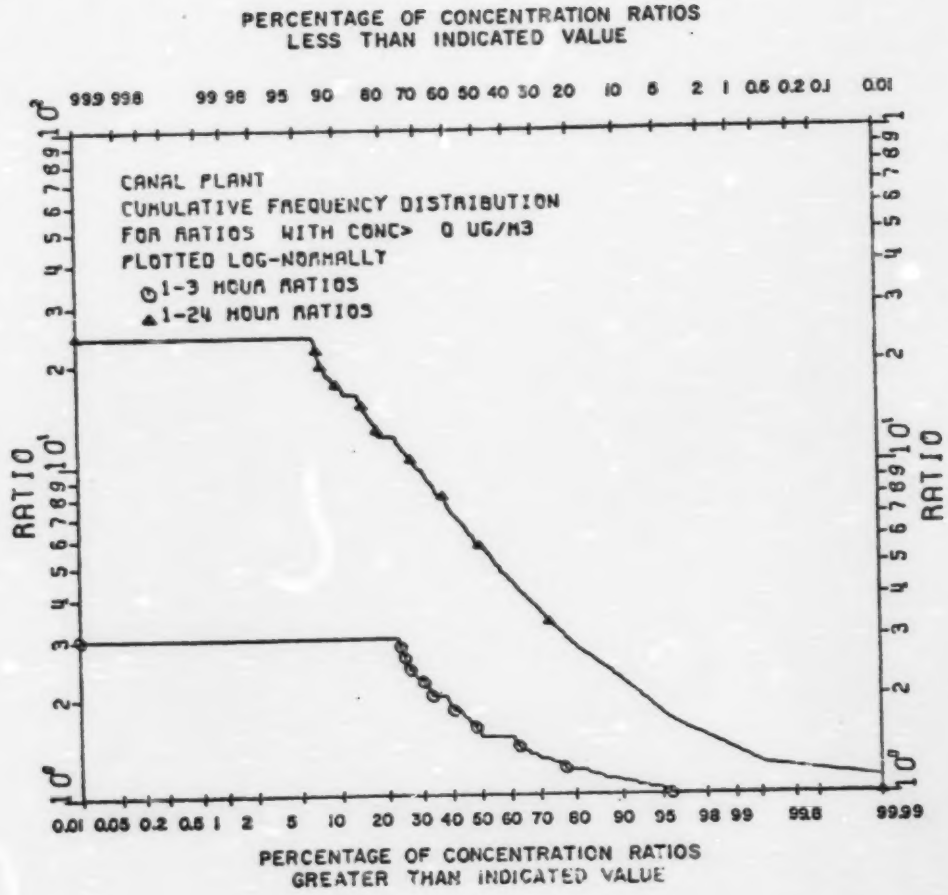
PERCENTAGE OF CONCENTRATION RATIOS
LESS THAN INDICATED VALUE
99.9 99.8 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.01
CANAL PLANT
CUMULATIVE FREQUENCY DISTRIBUTION
FOR RATIOS WITH CONC> 0 UG/M3
PLOTTED LOG-NORMALLY
1-3 HOUR RATIOS
1-24 HOUR RATIOS
RATIO
RATIO
0.01 0.05 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.99
PERCENTAGE OF CONCENTRATION RATIOS
GREATER THAN INDICATED VALUE

Figure 8. Canal Plant cumulative frequency distribution of ratios of peak to mean concentrations for all cases

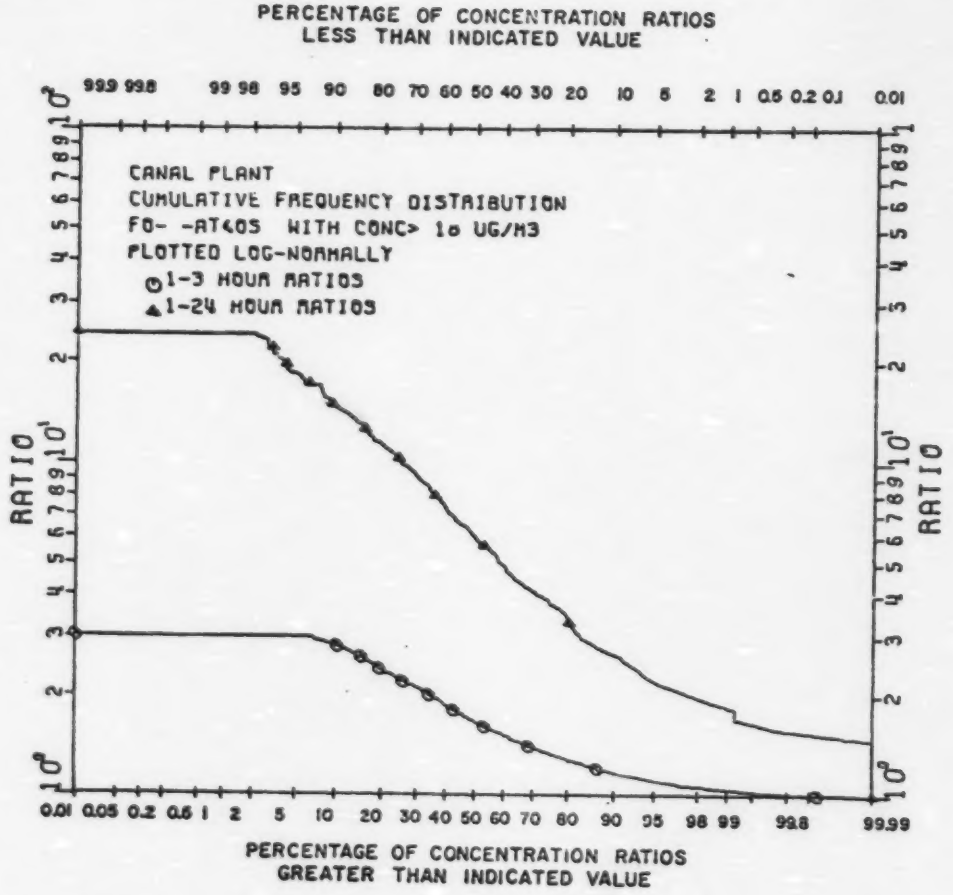
PERCENTAGE OF CONCENTRATION RATIOS
LESS THAN INDICATED VALUE
99.9 99.8 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.01
CANAL PLANT
CUMULATIVE FREQUENCY DISTRIBUTION
FO- -AT<0S WITH CONC> 1σ UG/M3
PLOTTED LOG-NORMALLY
1-3 HOUR RATIOS
1-24 HOUR RATIOS
RATIO
RATIO
0.01 0.05 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.99
PERCENTAGE OF CONCENTRATION RATIOS
GREATER THAN INDICATED VALUE

Figure 9. Canal Plant cumulative frequency distribution of ratios of peak to mean concentrations for cases where the peak concentrations are greater than 18 $\mu g/m^3$; 18 $\mu g/m^3$ is the 95th percentile of the 1-hour concentrations

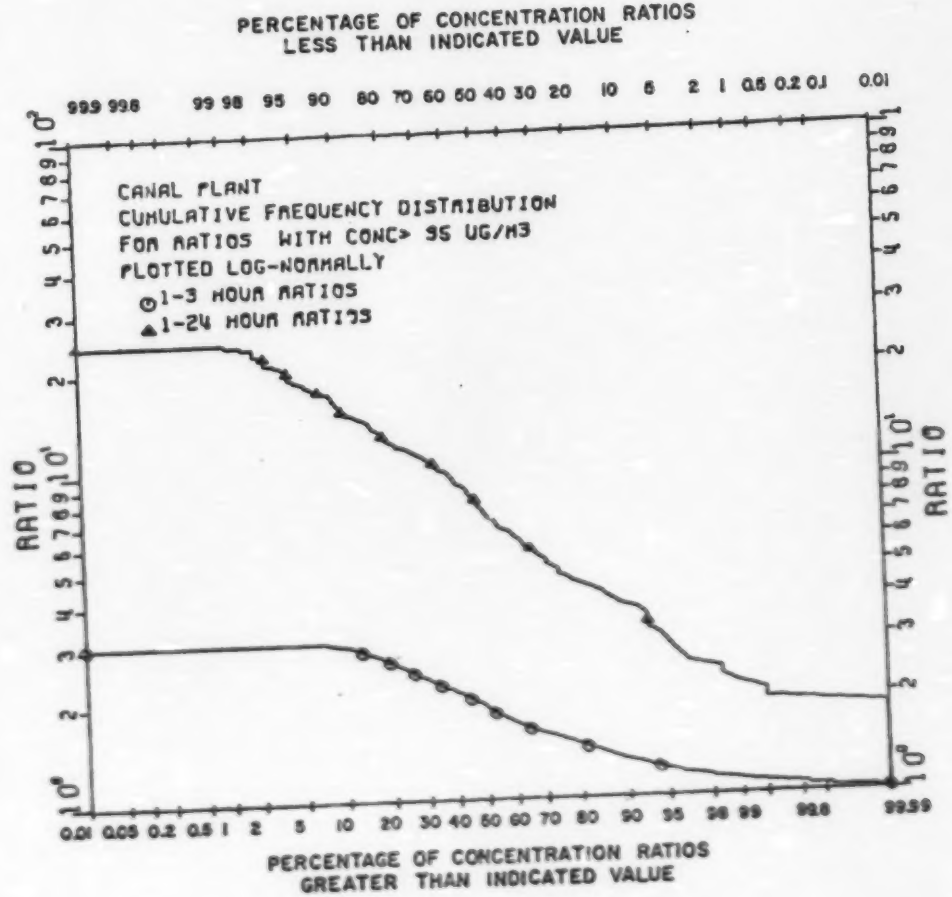
PERCENTAGE OF CONCENTRATION RATIOS
LESS THAN INDICATED VALUE
99.9 99.8 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.01
CANAL PLANT
CUMULATIVE FREQUENCY DISTRIBUTION
FOR RATIOS WITH CONC> 35 UG/M3
PLOTTED LOG-NORMALLY
⊙1-3 HOUR RATIOS
▲1-24 HOUR RATIOS
RATIO
RATIO
0.01 0.05 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.99
PERCENTAGE OF CONCENTRATION RATIOS
GREATER THAN INDICATED VALUE

Figure 10. Canal Plant cumulative frequency distribution of ratios of peak to mean concentrations for cases where the peak concentrations are greater than 35 $\mu g/m^3$; 35 $\mu g/m^3$ is the 98th percentile of the 1-hour concentrations

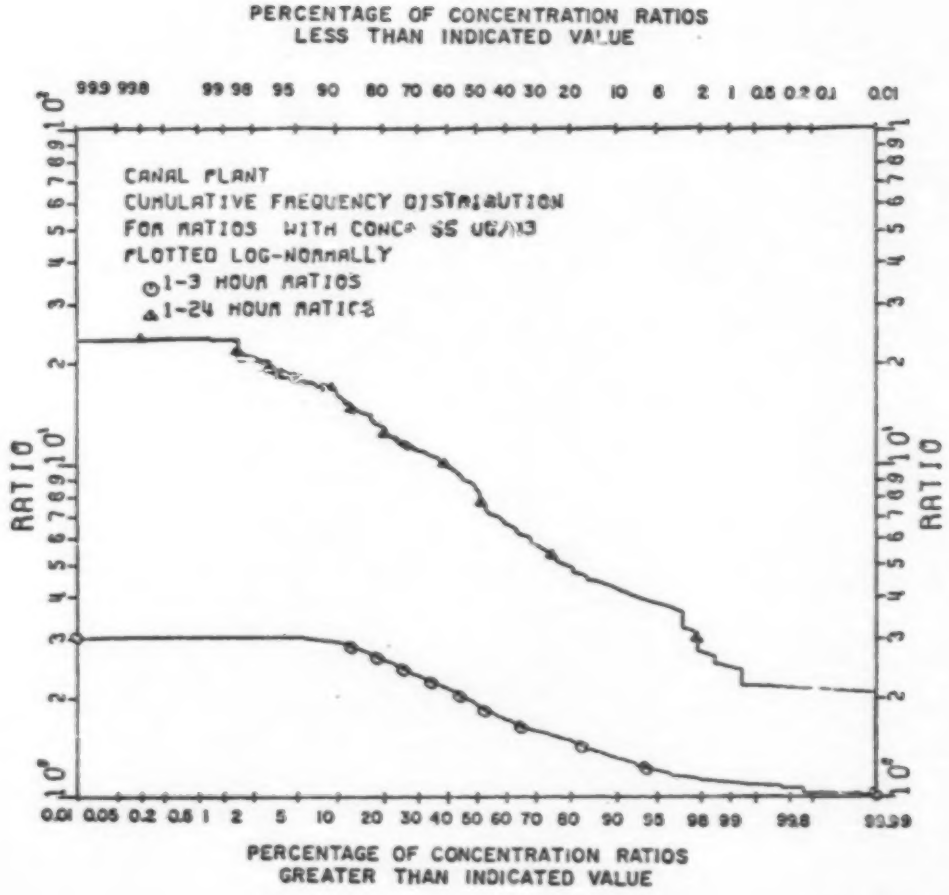
PERCENTAGE OF CONCENTRATION RATIOS
LESS THAN INDICATED VALUE
999 998 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.01
CANAL PLANT
CUMULATIVE FREQUENCY DISTRIBUTION
FOR RATIOS WITH CONC
PLOTTED LOG-NORMALLY
1-3 HOUR RATIOS
1-24 HOUR RATIOS
RATIO
0.01 0.05 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.99
PERCENTAGE OF CONCENTRATION RATIOS
GREATER THAN INDICATED VALUE

Figure 11. Canal Plant cumulative frequency distribution of ratios of peak to mean concentrations for cases where the peak concentrations are greater than 55 $\mu g/m^3$; 55 $\mu g/m^3$ is the 99th percentile of the 1-hour concentrations

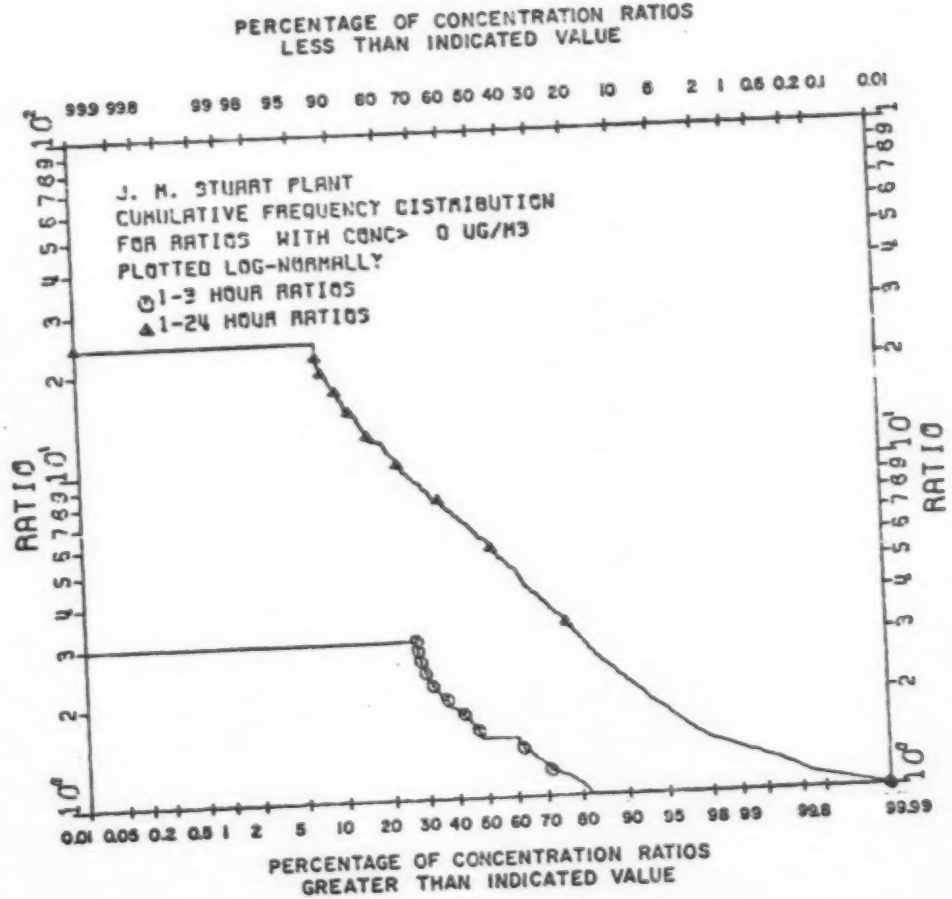
PERCENTAGE OF CONCENTRATION RATIOS
LESS THAN INDICATED VALUE
99.9 99.8 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.01
J. M. STUART PLANT
CUMULATIVE FREQUENCY DISTRIBUTION
FOR RATIOS WITH CONC> 0 UG/M3
PLOTTED LOG-NORMALLY
1-3 HOUR RATIOS
1-24 HOUR RATIOS
RATIO
RATIO
0.01 0.05 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.99
PERCENTAGE OF CONCENTRATION RATIOS
GREATER THAN INDICATED VALUE

Figure 12. J. M. Stuart Plant cumulative frequency distribution of ratios of peak to mean concentrations for all cases

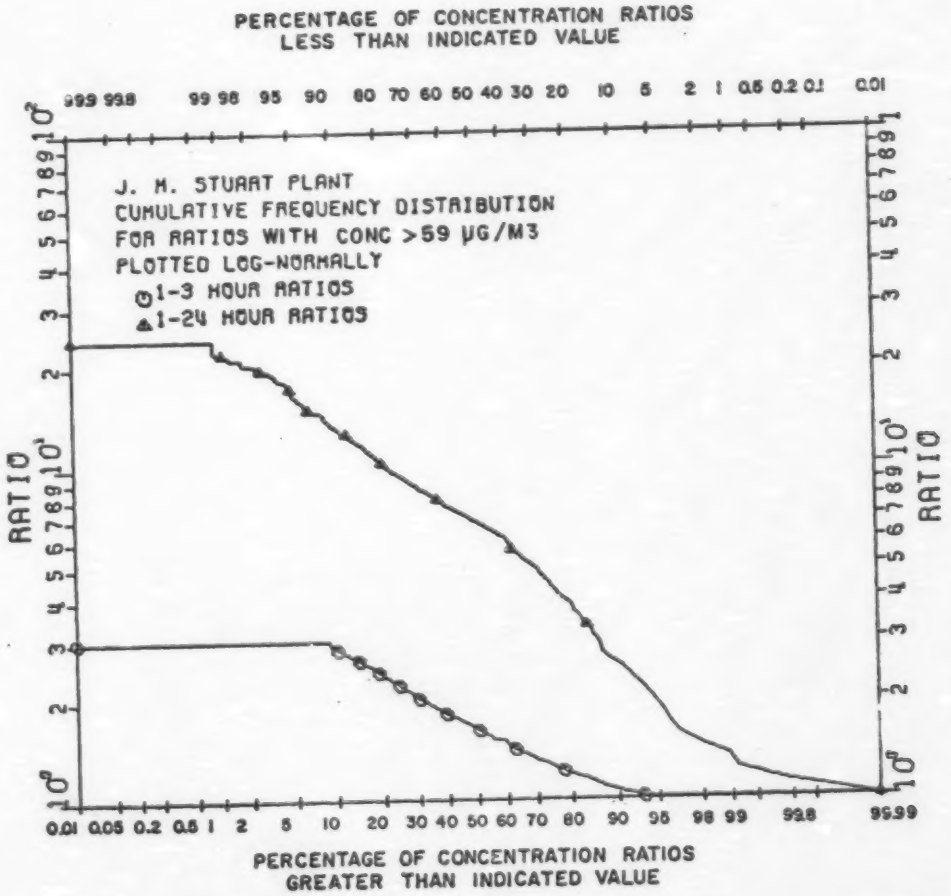
PERCENTAGE OF CONCENTRATION RATIOS
LESS THAN INDICATED VALUE
99.9 99.8 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.01
J. M. STUART PLANT
CUMULATIVE FREQUENCY DISTRIBUTION
FOR RATIOS WITH CONC >59 µG/M3
PLOTTED LOG-NORMALLY
1-3 HOUR RATIOS
1-24 HOUR RATIOS
RATIO
RATIO
0.01 0.05 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.99
PERCENTAGE OF CONCENTRATION RATIOS
GREATER THAN INDICATED VALUE

Figure 13. J. M. Stuart Plant cumulative frequency distribution of ratios of peak to mean concentrations for cases where the peak concentrations are greater than 59 $\mu g/m^3$; 59 $\mu g/m^3$ is the 95th percentile of the 1-hour concentrations

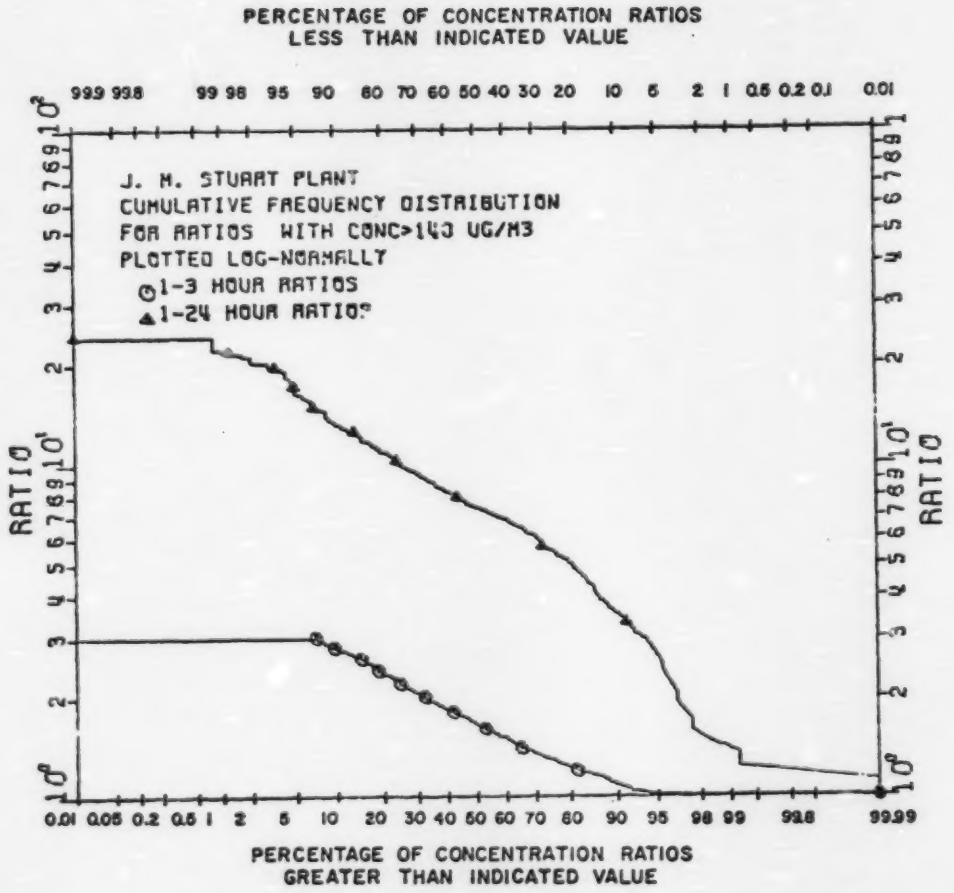
PERCENTAGE OF CONCENTRATION RATIOS
LESS THAN INDICATED VALUE
99.9 99.8 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.01
J. M. STUART PLANT
CUMULATIVE FREQUENCY DISTRIBUTION
FOR RATIOS WITH CONC>140 UG/M3
PLOTTED LOG-NORMALLY
⊙1-3 HOUR RATIOS
▲1-24 HOUR RATIOS
RATIO
RATIO
0.01 0.05 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.99
PERCENTAGE OF CONCENTRATION RATIOS
GREATER THAN INDICATED VALUE

Figure 14. J. M. Stuart Plant cumulative frequency distribution of ratios of peak to mean concentrations for cases where the peak concentrations are greater than 140 $\mu g/m^3$; 140 $\mu g/m^3$ is the 98th percentile of the 1-hour concentrations.

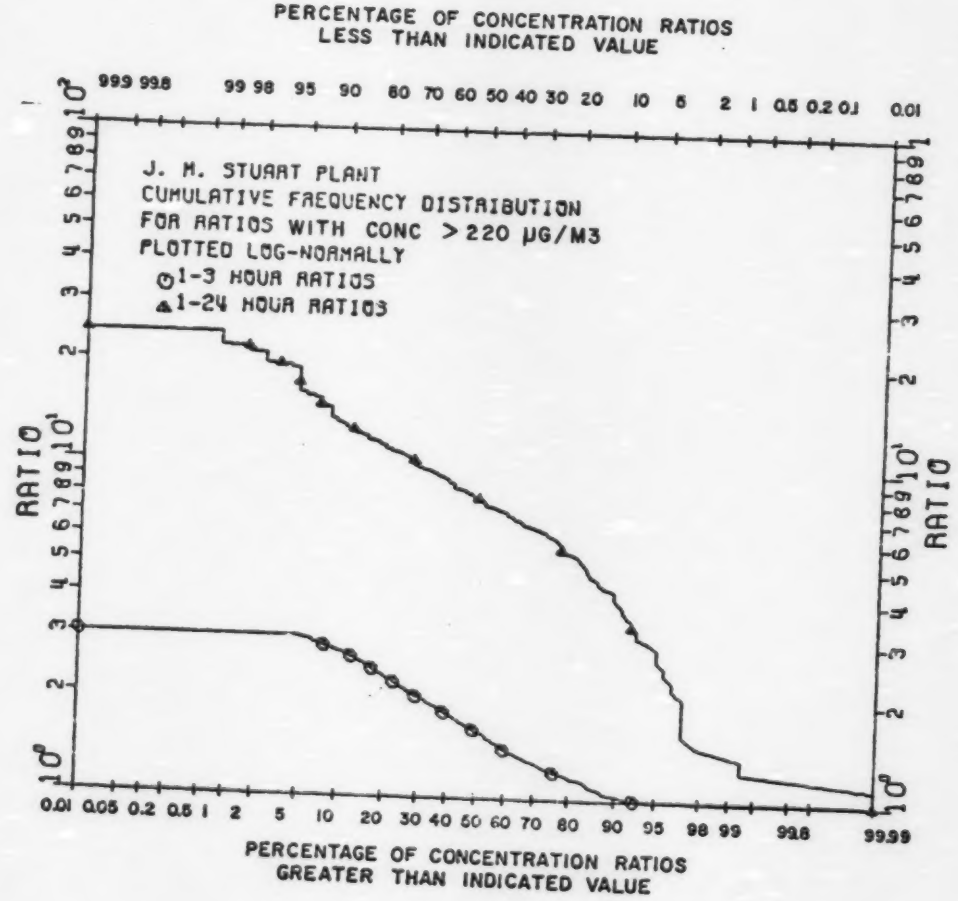
PERCENTAGE OF CONCENTRATION RATIOS
LESS THAN INDICATED VALUE
999 998
99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.01
J. M. STUART PLANT
CUMULATIVE FREQUENCY DISTRIBUTION
FOR RATIOS WITH CONC > 220 µG/M3
PLOTTED LOG-NORMALLY
⊙1-3 HOUR RATIOS
▲1-24 HOUR RATIOS
RATIO
0.01 0.05 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.99
PERCENTAGE OF CONCENTRATION RATIOS
GREATER THAN INDICATED VALUE

Figure 15. J. M. Stuart Plant cumulative frequency distribution of ratios of peak to mean concentrations for cases where the peak concentrations are greater than 220 $\mu g/m^3$; 220 $\mu g/m^3$ is the 99th percentile of the 1-hour concentrations

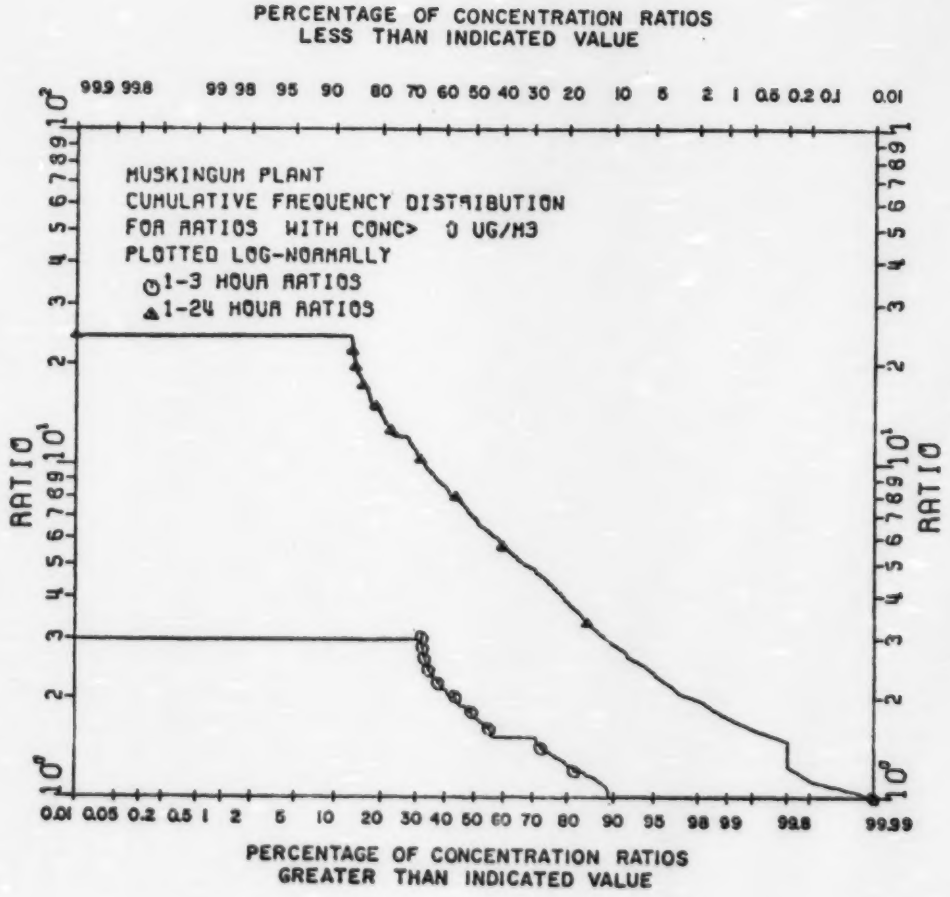
PERCENTAGE OF CONCENTRATION RATIOS
LESS THAN INDICATED VALUE
99.9 99.8 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.01
MUSKINGUM PLANT
CUMULATIVE FREQUENCY DISTRIBUTION
FOR RATIOS WITH CONC> 0 UG/M3
PLOTTED LOG-NORMALLY
1-3 HOUR RATIOS
1-24 HOUR RATIOS
RATIO
RATIO
0.01 0.05 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.99
PERCENTAGE OF CONCENTRATION RATIOS
GREATER THAN INDICATED VALUE

Figure 16. Muskingum Plant cumulative frequency distribution of ratios of peak to mean concentrations for all cases

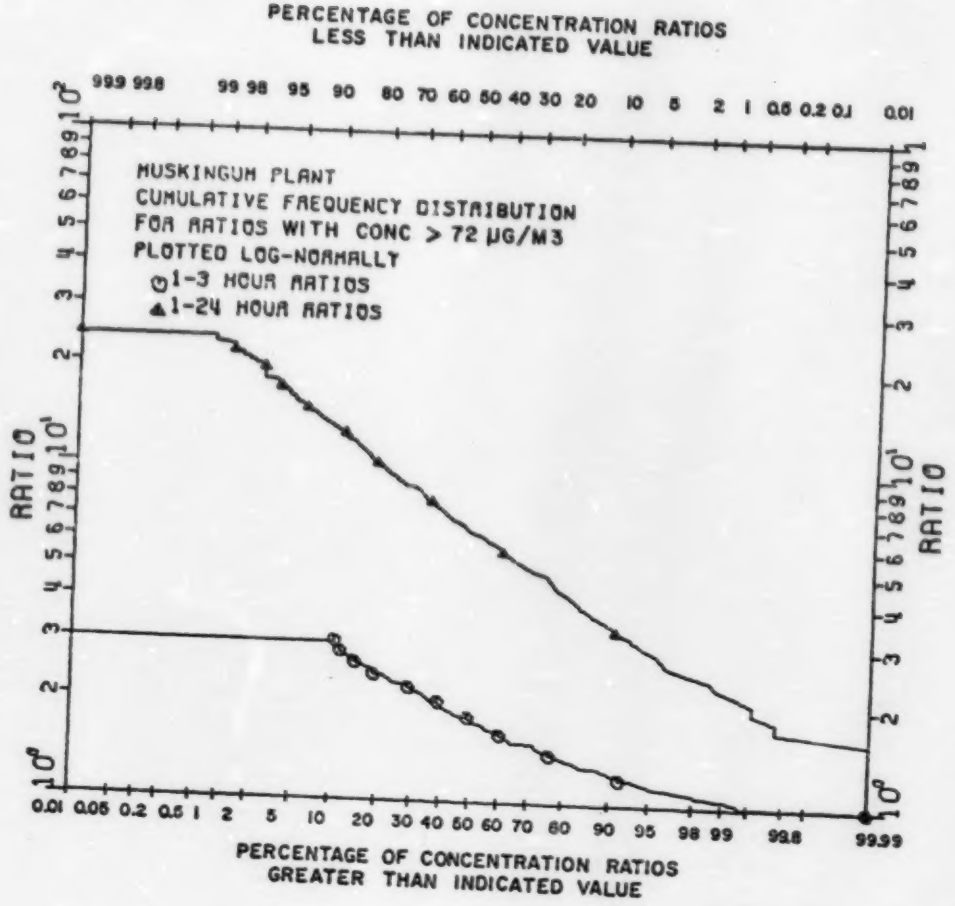
PERCENTAGE OF CONCENTRATION RATIOS
LESS THAN INDICATED VALUE
99.9 99.8 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.01
MUSKINGUM PLANT
CUMULATIVE FREQUENCY DISTRIBUTION
FOR RATIOS WITH CONC > 72 µG/M3
PLOTTED LOG-NORMALLY
1-3 HOUR RATIOS
1-24 HOUR RATIOS
RATIO
0.01 0.05 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.99
PERCENTAGE OF CONCENTRATION RATIOS
GREATER THAN INDICATED VALUE

Figure 17. Muskingum Plant cumulative frequency distribution of ratios of peak to mean concentrations for cases where the peak concentrations are greater than 72 $\mu g/m^3$; 72 $\mu g/m^3$ is the 95th percentile of the 1-hour concentrations

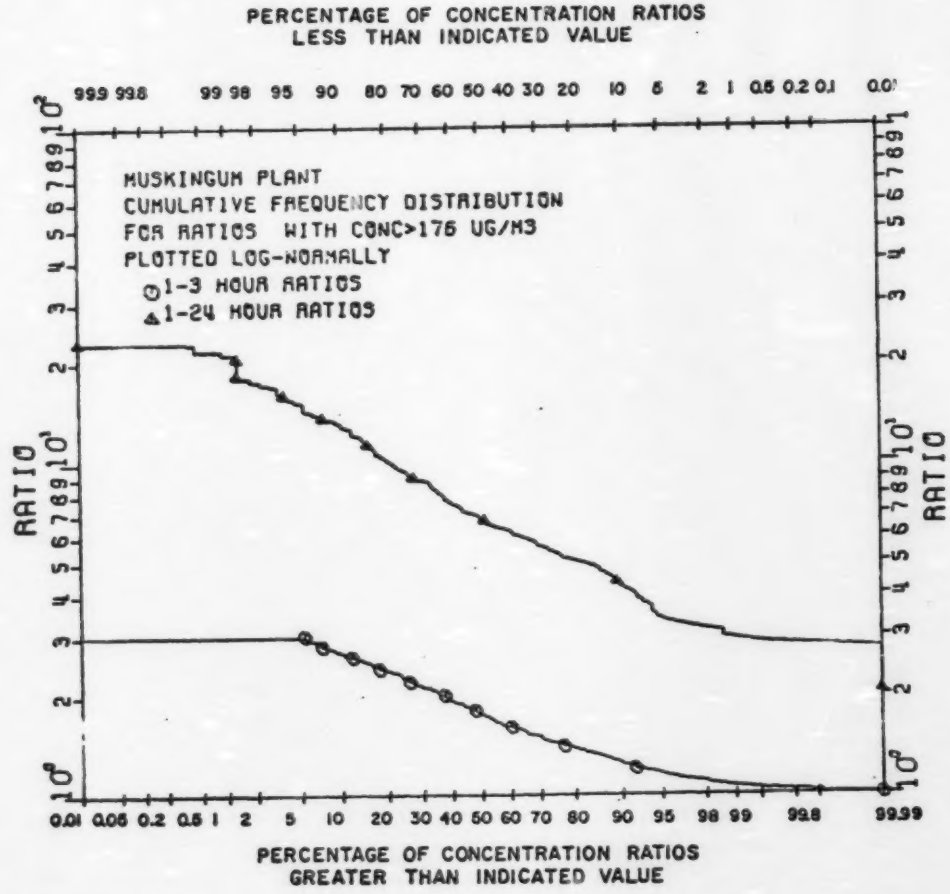
PERCENTAGE OF CONCENTRATION RATIOS
LESS THAN INDICATED VALUE
99.9 99.8 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.0
MUSKINGUM PLANT
CUMULATIVE FREQUENCY DISTRIBUTION
FOR RATIOS WITH CONC>176 UG/M3
PLOTTED LOG-NORMALLY
1-3 HOUR RATIOS
1-24 HOUR RATIOS
RATIO
RATIO
0.01 0.05 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.99
PERCENTAGE OF CONCENTRATION RATIOS
GREATER THAN INDICATED VALUE

Figure 18. Muskingum Plant cumulative frequency distribution of ratios of peak to mean concentrations for cases where the peak concentrations are greater than 176 $\mu g/m^3$; 176 $\mu g/m^3$ is the 98th percentile of the 1-hour concentrations

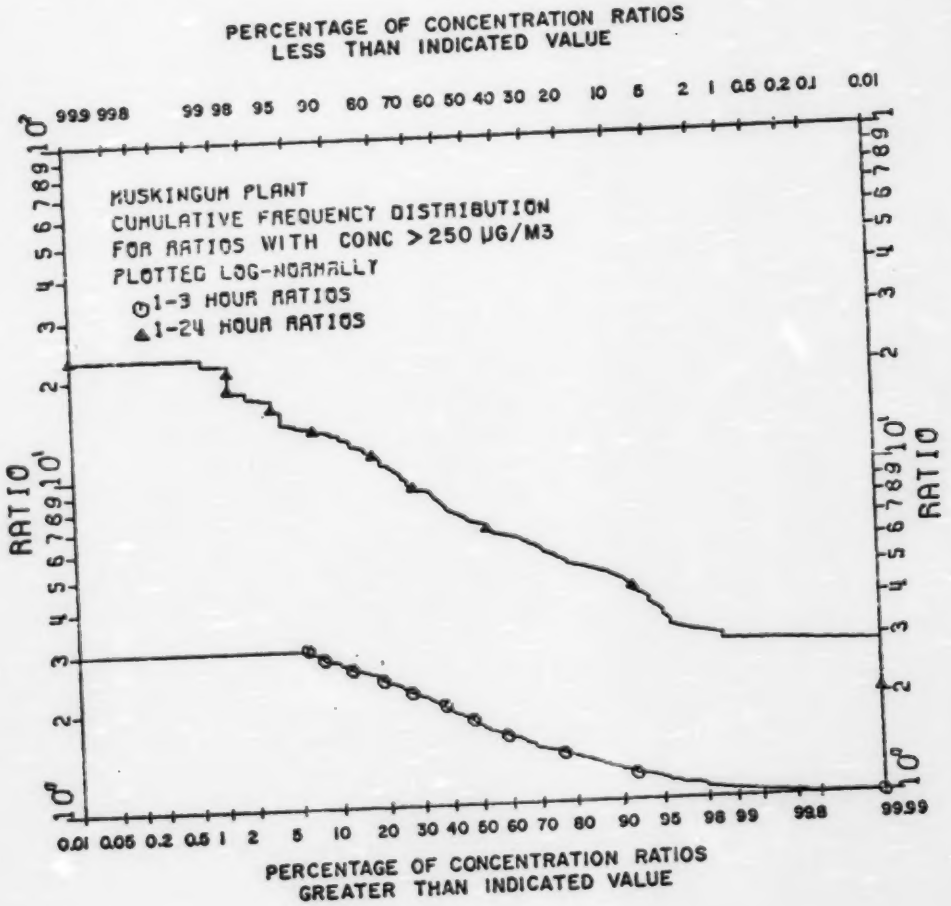
PERCENTAGE OF CONCENTRATION RATIOS
LESS THAN INDICATED VALUE
999 998 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.01
MUSKINGUM PLANT
CUMULATIVE FREQUENCY DISTRIBUTION
FOR RATIOS WITH CONC > 250 UG/M3
PLOTTED LOG-NORMALLY
1-3 HOUR RATIOS
1-24 HOUR RATIOS
RATIO
RATIO
0.01 0.05 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.99
PERCENTAGE OF CONCENTRATION RATIOS
GREATER THAN INDICATED VALUE

Figure 19. Muskingum Plant cumulative frequency distribution of ratios of peak to mean concentrations for cases where the peak concentrations are greater than 250 $\mu g/m^3$; 250 $\mu g/m^3$ is the 99th percentile of the 1-hour concentrations

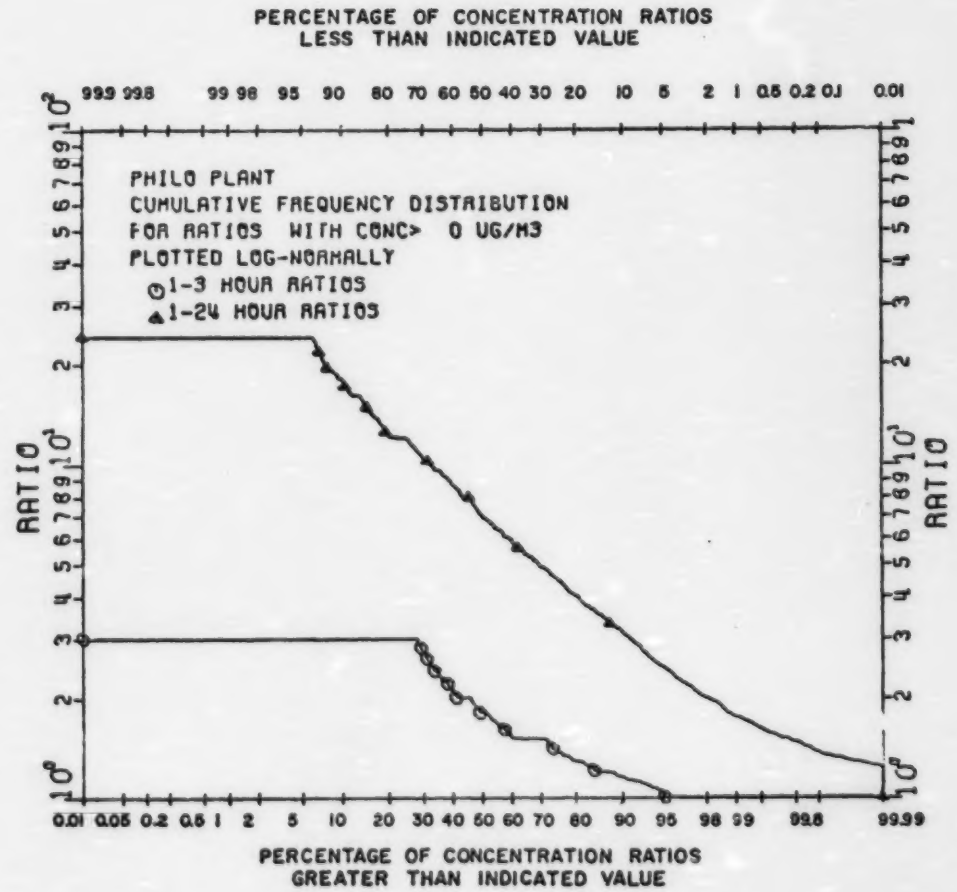
PERCENTAGE OF CONCENTRATION RATIOS
LESS THAN INDICATED VALUE
99.9 99.8 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.01
PHILO PLANT
CUMULATIVE FREQUENCY DISTRIBUTION
FOR RATIOS WITH CONC> 0 UG/M3
PLOTTED LOG-NORMALLY
1-3 HOUR RATIOS
1-24 HOUR RATIOS
RATIO
RATIO
0.01 0.05 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.99
PERCENTAGE OF CONCENTRATION RATIOS
GREATER THAN INDICATED VALUE

Figure 20. Philo Plant cumulative frequency distribution of ratios of peak to mean concentrations for all cases

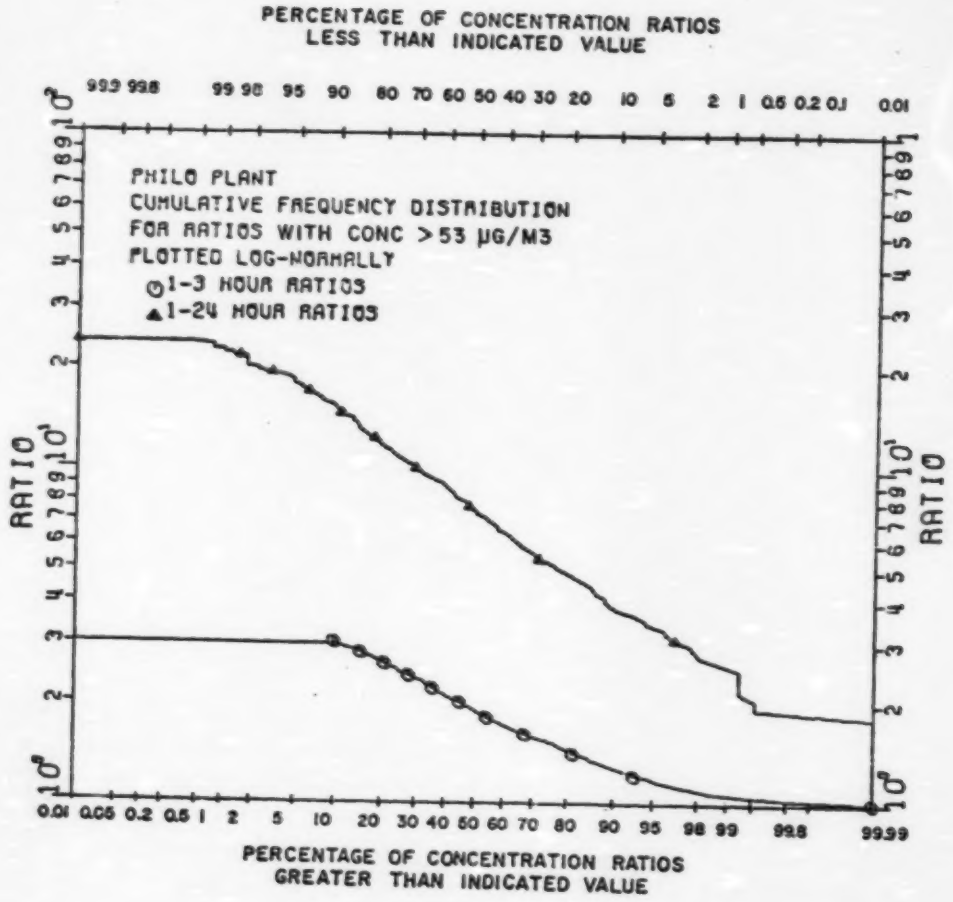
PERCENTAGE OF CONCENTRATION RATIOS
LESS THAN INDICATED VALUE
99.9 99.8 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.01
PHILO PLANT
CUMULATIVE FREQUENCY DISTRIBUTION
FOR RATIOS WITH CONC > 53 µG/M3
PLOTTED LOG-NORMALLY
⊙1-3 HOUR RATIOS
▲1-24 HOUR RATIOS
RATIO
RATIO
0.01 0.05 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.99
PERCENTAGE OF CONCENTRATION RATIOS
GREATER THAN INDICATED VALUE

Figure 21. Philo Plant cumulative frequency distribution of ratios of peak to mean concentrations for cases where the peak concentrations are greater than 53 $\mu g/m^3$; 53 $\mu g/m^3$ is the 95th percentile of the 1-hour concentrations

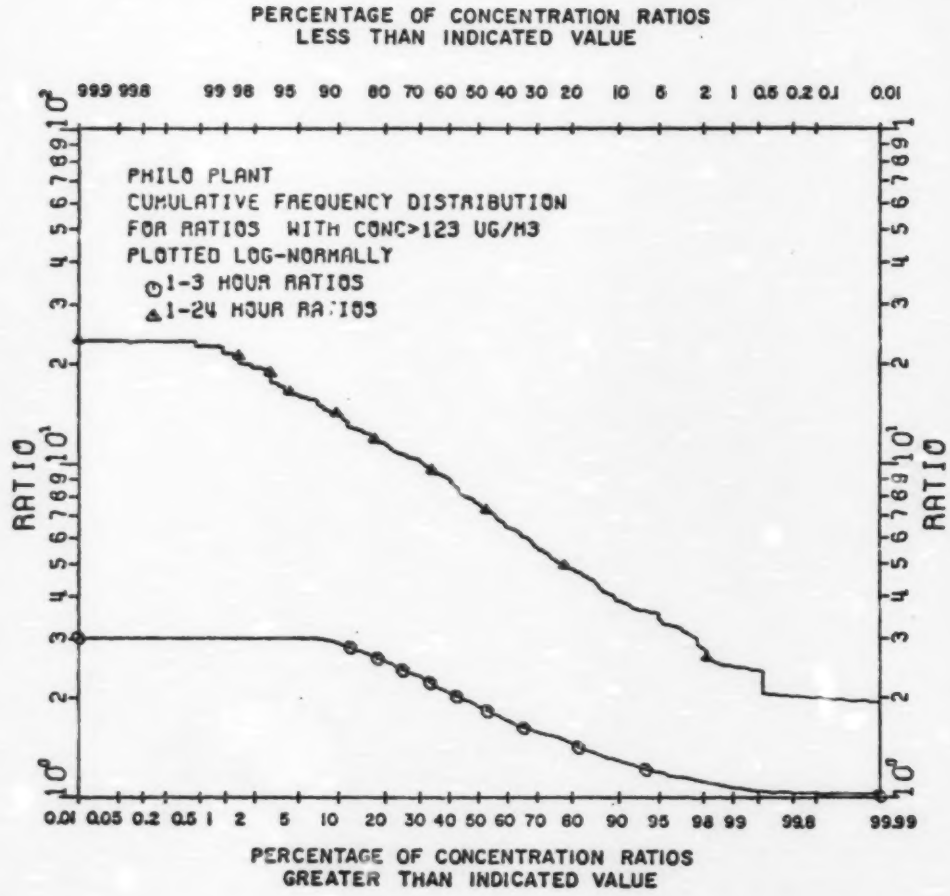
PERCENTAGE OF CONCENTRATION RATIOS
LESS THAN INDICATED VALUE
99.9 99.8 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.01
PHILO PLANT
CUMULATIVE FREQUENCY DISTRIBUTION
FOR RATIOS WITH CONC>123 UG/M3
PLOTTED LOG-NORMALLY
1-3 HOUR RATIOS
1-24 HOUR RATIOS
RATIO
RATIO
0.01 0.05 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.99
PERCENTAGE OF CONCENTRATION RATIOS
GREATER THAN INDICATED VALUE

Figure 22. Philo Plant cumulative frequency distribution of ratios of peak to mean concentrations for cases where the peak concentrations are greater than 123 $\mu g/m^3$; 123 $\mu g/m^3$ is the 98th percentile of the 1-hour concentrations

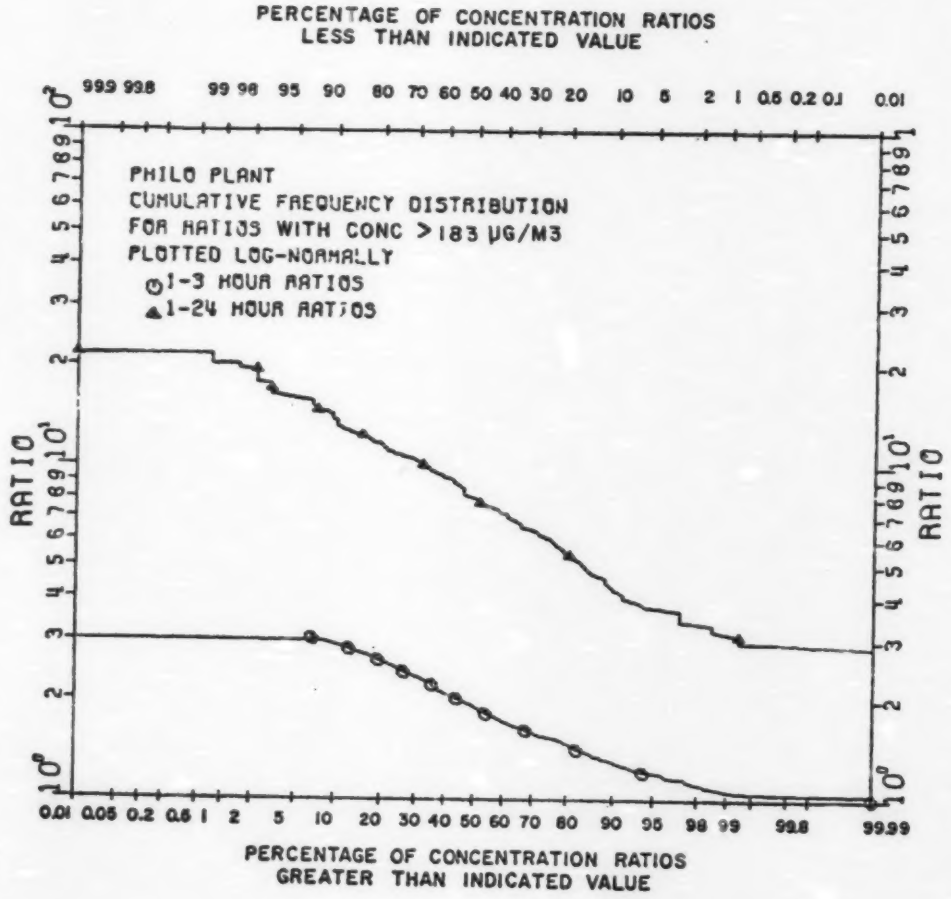
PERCENTAGE OF CONCENTRATION RATIOS
LESS THAN INDICATED VALUE
99.9 99.8 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.01
PHILO PLANT
CUMULATIVE FREQUENCY DISTRIBUTION
FOR RATIOS WITH CONC >183 µG/M3
PLOTTED LOG-NORMALLY
⊙1-3 HOUR RATIOS
▲1-24 HOUR RATIOS
RATIO
0.01 0.05 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.99
PERCENTAGE OF CONCENTRATION RATIOS
GREATER THAN INDICATED VALUE

Figure 23. Philo Plant cumulative frequency distribution of ratios of peak to mean concentrations for cases where the peak concentrations are greater than 183 $\mu g/m^3$; 183 $\mu g/m^3$ is the 99th percentile of the 1-hour concentrations

Table 4. STATISTICS FOR PEAK TO MEAN RATIO DISTRIBUTIONS

Plant	Ratio	Lower percentile cutoff for peak concentration, %	Peak concentration cutoff, ug/m^3	Arithmetic mean	Arithmetic standard deviation	Geometric mean	Geometric standard deviation	50th percentile	Peak-ratio correlation	95% confidence interval of correlation		Number of values	Significant to 95%
Canal	1-3 hr	0	0	1.868	0.7175	1.739	1.453	1.54	-0.02517	-0.0113	-0.0390	20,072	Yes
		95	18	1.829	0.5814	1.743	1.361	1.67	0.12310	0.1593	0.0866	2,818	Yes
		98	35	1.978	0.5694	1.897	1.337	1.89	-0.00727	0.0473	-0.0618	1,293	No
		99	55	1.977	0.5595	1.899	1.330	1.89	-0.00951	0.0578	-0.0767	850	No
	1-24 hr	0	0	7.827	6.1361	5.892	2.135	5.60	0.02344	0.0819	-0.0352	1,119	No
		95	18	7.466	5.033	6.090	1.892	5.90	0.16367	0.2599	0.0643	381	Yes
		98	35	8.634	4.791	7.441	1.740	7.40	0.06409	0.2000	-0.0743	203	No
		99	55	8.972	4.546	7.915	1.663	8.25	0.02142	0.1844	-0.1427	144	No
Stuart	1-3 hr	0	0	1.852	0.7742	1.699	1.512	1.50	-0.05517	-0.0453	-0.0715	22,278	Yes
		95	59	1.761	0.6138	1.662	1.402	1.61	0.00353	0.3609	-0.0290	3,623	No
		98	140	1.778	0.5965	1.685	1.387	1.63	-0.04397	0.0079	-0.0956	1,427	No
		99	220	1.722	0.5937	1.627	1.396	1.58	0.02782	0.0966	-0.0412	809	No
	1-24 hr	0	0	7.709	5.945	5.917	2.078	6.00	0.00146	0.0538	-0.0509	1,402	No
		95	59	7.456	4.353	6.268	1.855	6.75	0.13190	0.2191	0.0426	477	Yes
		98	140	8.127	4.165	7.114	1.722	7.35	0.03804	0.1606	-0.0857	253	No
		99	220	8.381	4.051	7.406	1.704	7.70	0.00010	0.1654	-0.1652	141	No
Muskingum	1-3 hr	0	0	1.991	0.7600	1.847	1.480	1.75	-0.07783	-0.0619	-0.0937	15,059	Yes
		95	72	1.882	0.5671	1.802	1.342	1.76	-0.03262	0.0044	-0.0696	2,797	No
		98	176	1.857	0.5287	1.786	1.322	1.75	-0.03310	0.0250	-0.0910	1,140	No
		99	250	1.859	0.5398	1.785	1.329	1.73	-0.06170	0.0127	-0.1354	696	No
	1-24 hr	0	0	9.232	6.785	7.190	2.032	6.75	-0.15123	-0.0929	-0.2085	1,100	Yes
		95	72	7.396	4.027	6.505	1.653	6.35	0.06867	0.1628	-0.0267	424	No
		98	176	7.723	3.541	7.053	1.521	6.70	0.01758	0.1463	-0.1118	231	No
		99	250	7.957	3.517	7.304	1.506	6.90	-0.06609	0.0909	-0.2200	158	No
Philo	1-3 hr	0	0	2.004	0.7217	1.873	1.448	1.80	-0.03525	-0.0214	-0.0490	20,142	Yes
		95	53	1.986	0.5862	1.901	1.348	1.88	-0.01296	0.0211	-0.0470	3,315	No
		98	123	1.964	0.5600	1.886	1.332	1.88	0.01974	0.0714	-0.0320	1,437	No
		99	183	1.976	0.5648	1.896	1.335	1.89	0.00985	0.0786	-0.0589	813	No
	1-24 hr	0	0	8.767	5.775	7.158	1.902	6.98	-0.04030	0.0175	-0.0978	1,152	No
		95	53	8.332	4.337	7.337	1.661	7.30	0.04850	0.1431	-0.0469	424	No
		98	123	8.290	4.005	7.410	1.616	7.52	0.10430	0.2322	-0.0272	224	No
		99	183	8.459	3.632	7.725	1.541	7.79	0.12208	0.2817	-0.0441	141	No

SECTION IV

COMPARISON WITH PREVIOUS STUDIES

A useful mechanism for the analysis of peak to mean concentration ratios is the fluctuating plume dispersion model first suggested by Gifford.[6] In this model the plume is composed of a number of contiguous disk elements perpendicular to the mean plume axis. The center of any one of these disks will be laterally displaced from the mean plume axis by a distance D given by

$$D = \frac{\sum_{i=1}^{n} y_i}{n} \qquad (1)$$

where y_i = the distance of particle i from the mean plume axis.

The mean square distance, Y^2, of each of the particles within the disk element from the center of the disk element itself is

$$Y^2 = \frac{\sum_{i=1}^{n} (y_i - D)^2}{n} \qquad (2)$$

The ensamble average of Y^2, the plume spreading parameter, may be written as follows:

$$\overline{Y^2} = \overline{y^2} - \overline{D^2} \qquad (3)$$

where

$$\overline{y^2} = \frac{\sum_{i=1}^{n} y_i^2}{n}$$

$$\overline{D^2} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} y_i y_j}{n^2}$$

The plume meandering parameter $\overline{D^2}$ reduces to the following expression:

$$\overline{D^2} = \frac{n\,\overline{y^2}}{n^2} + \frac{n(n-1)}{n^2}\,\overline{y_i y_j} \tag{4}$$

which for a large number of particles becomes

$$\overline{D^2} \rightarrow \overline{y_i y_j} \tag{5}$$

Equation 3 may therefore be written in terms of two particle statistics to give

$$\overline{Y^2} = \overline{y^2} - \overline{y_i y_j} \tag{6}$$

As the diffusion time, or equivalently, the distance from the source increases, it can be shown by means of statistical theories of turbulent diffusion that the plume spreading parameter $\overline{Y^2}$ becomes independent of $\overline{y_i y_j}$ and may be better described in terms of one particle statistics or

K theory. Based upon this analysis we may infer that $\overline{y_i y_i}$ and therefore $\overline{D^2}$ will approach a constant value at large distances from the source. This result implies a smaller average peak to mean ratio for increasing receptor distances from the source. This trend toward lower peak to mean ratios at greater distances from the source is not inconsistent with the results of the present study as shown in Table 5. Further analysis using individual receptor locations would be required to show whether these results are statistically significant.

Table 5. COMPARISON OF PEAK TO MEAN CONCENTRATION RATIOS FOR DIFFERENT SOURCE RECEPTOR DISTANCES

Plant	Mean source, receptor distance, km	Geometric mean of distributions, peak to mean ratio for 99th percentile peak concentration	
		1- to 3-hour	1- to 24-hour
Canal	2.6	1.90	7.91
Stuart	6.9	1.63	7.41
Muskingum	9.4	1.78	7.30
Philo	3.8	1.90	7.72

Most studies of concentration ratio distributions have involved peak values averaged over periods of only a few minutes. One such evaluation of SO_2 concentration ratio distributions was carried out by the Tennessee Valley Authority (TVA)[7] in the vicinity of the Paradise Power Plant with data taken over a 2-1/2 year period from January 1968 through June 1970. During this time period, 14 SO_2 monitors located in the 22-1/2 degree prevailing downwind sector were operated on a continuous basis. All but one of the stations were located within a distance of from 3 to 10 km from the plant. From the concentration data peak-to-1-hour average and peak-to-24-hour average concentration ratios were obtained for each measuring instrument. The highest 5-minute average concentration that occurred during a particular hour was considered to be the peak concentration for that hour. To avoid interference from background contributions,

those hours with average concentrations less than 0.10 ppm were excluded from the analysis. The resulting ratio distributions were analyzed according to stability type and receptor distance from the source. Stability assignments (unstable, neutral, stable) were made according to the potential temperature gradient which was obtained from hourly temperature measurements at 13 m and 110 m meteorological tower levels.

Although the procedure for background subtraction and determination of peak concentrations was different from those used in our study, their results correlate quite well with our findings. In particular, they found a general decrease in concentration ratios (both 1- to 3-hour and 1- to 24-hour) for increasing distance from the source.

SECTION V

CONCLUSION

Through a reexamination of our previous analyses of time-concentration relationships we have made our results more applicable to the estimation of maximum 3-hour and 24-hour concentrations based upon predictions of maximum 1-hour concentrations. By restricting our analysis of peak to mean ratio distributions to those cases in which the peak concentration was above a certain threshold level, we ensured that the resultant distribution statistics would be determined primarily by the combination of point source emission characteristics, meteorology and topography rather than spatial variations in the background concentration.

When this restriction was applied, both the 1- to 3-hour and 1- to 24-hour ratio distributions were found to follow more closely the log-normal distribution shape with an associated decrease in the standard geometric deviation as the peak 1-hour concentration threshold was increased. This reduction in the standard geometric deviation was especially significant for the 1- to 24-hour concentration ratios where it averaged 25 percent.

The magnitude of the standard geometric deviation is of considerable importance with regard to any future application of these ratios on an operational basis for the prediction of 3-hour and 24-hour concentrations. Estimates of yearly maximum 1-hour concentrations based upon EPA point source models are generally within 50 percent of measured values but estimates of 3-hour and 24-hour maximum concentrations obtained from an analysis of 1-hour predictions based upon an entire hourly year of meteorological data may differ by more than a factor of 2 from measured values.[2,3] If, on the other hand, the 3-hour and 24-hour maximum

concentrations are estimated through application of the geometric mean of the peak to mean ratio distribution, the accuracy of these predictions should be comparable to that of the 1-hour predictions except for the uncertainty associated with the width of the ratio distribution as parameterized by the standard geometric deviation. A determination of the relative merits of these two methods for estimation of maximum 3-hour and 24-hour concentrations must await the results of future model validation studies. Nevertheless, the ratio method obviously has an operational advantage in that it does not require the use of an entire year of meteorological data.

Finally, we should point out that in addition to the intrinsic spread of each ratio distribution, the geometric means will vary from one site to the next depending upon climatology, point source characteristics and receptor location. Based upon the results of the present study, it would appear that the 1- to 3-hour ratio distributions are more sensitive to variations in these parameters than the 1- to 24-hour distributions. A sufficient range of climatological regimes has not been encountered in this study to permit us to estimate the effect of these variables upon the ratio distributions. It should also be noted that the emission rates for the point sources in this study did not vary to an appreciable degree over the concentration averaging times used in the construction of the ratio distributions. For sources with significant emissions variations the peak to mean statistics should be modified to reflect the time dependence of the source function.

SECTION VI

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